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DEVELOPMENT AND EVALUATION OF PROTOTYPE REMOTE-CONTROLLED SODIUM-BONDING AND BOND-INSPECTION PROCESSES FOR EBR-II FUEL CYCLE FACILITY

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Reactor Engineering Division

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DEVELOPMENT AND EVALUATION OF PROTOTYPE REMOTE-CONTROLLED SODIUM-BONDING AND BOND-INSPECTION PROCESSES FOR EBR-II FUEL CYCLE FACILITY

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ABSTRACT

The EBR-II plant includes an integral, remote-controlled Fuel Cycle Facility wherein spent fuel elements are to be pyrometallurgically refined, refabricated, inspected, and reassembled for return to the reactor. This report describes the experimentally supported changes and refinements made in the prototype sodium-bonding and bond-inspection equipment to ensure: (1) acceptable fuel elements for the initial core loading; and (2) equally acceptable elements in production quantities in the parent installation. More specifically, the mode of imparting bonding energy to the fuel element was changed from a vibratory action to a series of timed impacts. This reflected an increase in the yield of acceptable elements and a reduction of machine operation time. A nondestructive, eddy-current instrument was developed and demonstrated as capable of detecting all defects in the liquid sodium bond. The diameter of the lower restrainer knob in the fuel element was increased to eliminate eccentricity as a contributor to erratic level of the sodium bond. As a result, the sodium level can be detected to a tolerance of $\pm\frac{1}{64}$ in. with a single, encircling eddy-current coil. Shrinkage voids in the sodium were not encountered. However, laboratory test data are presented in support of the conclusions that: (1) shrinkage voids can be promoted by improper cooling, even in initially void-free elements; and (2) the voids are transient in nature and do not permanently disturb the homogeneity of the sodium bond.

I. INTRODUCTION

The Experimental Breeder Reactor-II (see Fig. 1 for a sketch of the complex) is an unmoderated, heterogeneous, sodium-cooled reactor and power plant with a power output of 62.5 Mw of heat. The energy produced in the reactor is converted to 20 Mw of electricity through a conventional steam cycle. The reactor may be fueled with U^{235} or plutonium, and the plant includes an integral Fuel Cycle Facility. In this facility, spent fuel elements are removed from their respective subassemblies, processed, fabricated, inspected, reassembled by remote control, and returned to the reactor.

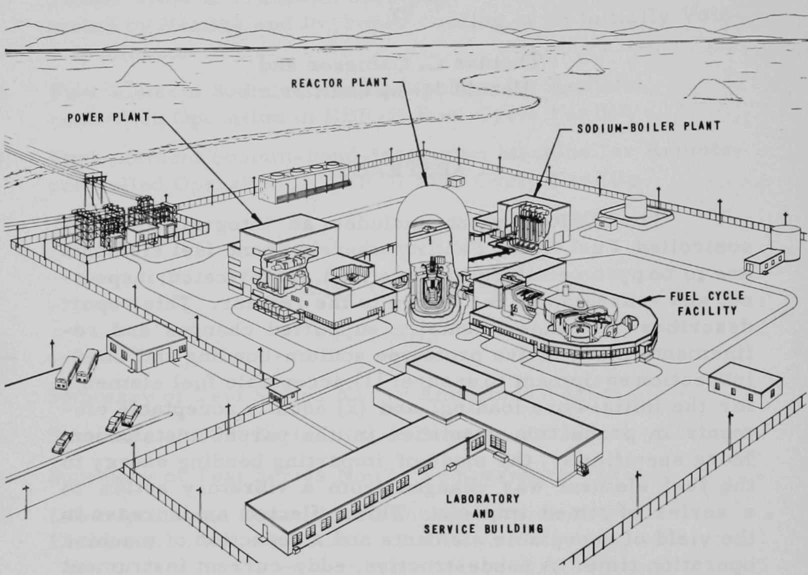

Fig. 1. Experimental Breeder Reactor-II Plant Complex
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The reactor is divided into three main zones: core, inner blanket, and outer blanket. Each zone is comprised of a number of right hexagonal subassemblies identified accordingly. A single subassembly size (2.290 in. across flats; 0.040 in. in wall thickness) is employed through the reactor. The upper end of each subassembly is identical, and all subassemblies are accommodated by the same remote-controlled handling and transfer devices.

Each subassembly contains a number of fuel elements, and/or blanket elements, of size and shape peculiar to that type of subassembly. The core subassembly (see Fig. 2) is comprised of three "active" sections: upper blanket, core, and lower blanket. The core section consists of 91 cylindrical fuel elements spaced on a triangular lattice by a single, helical rib on the outside of each element. The elements are supported within the subassembly by fastening their lower ends to a support grid.

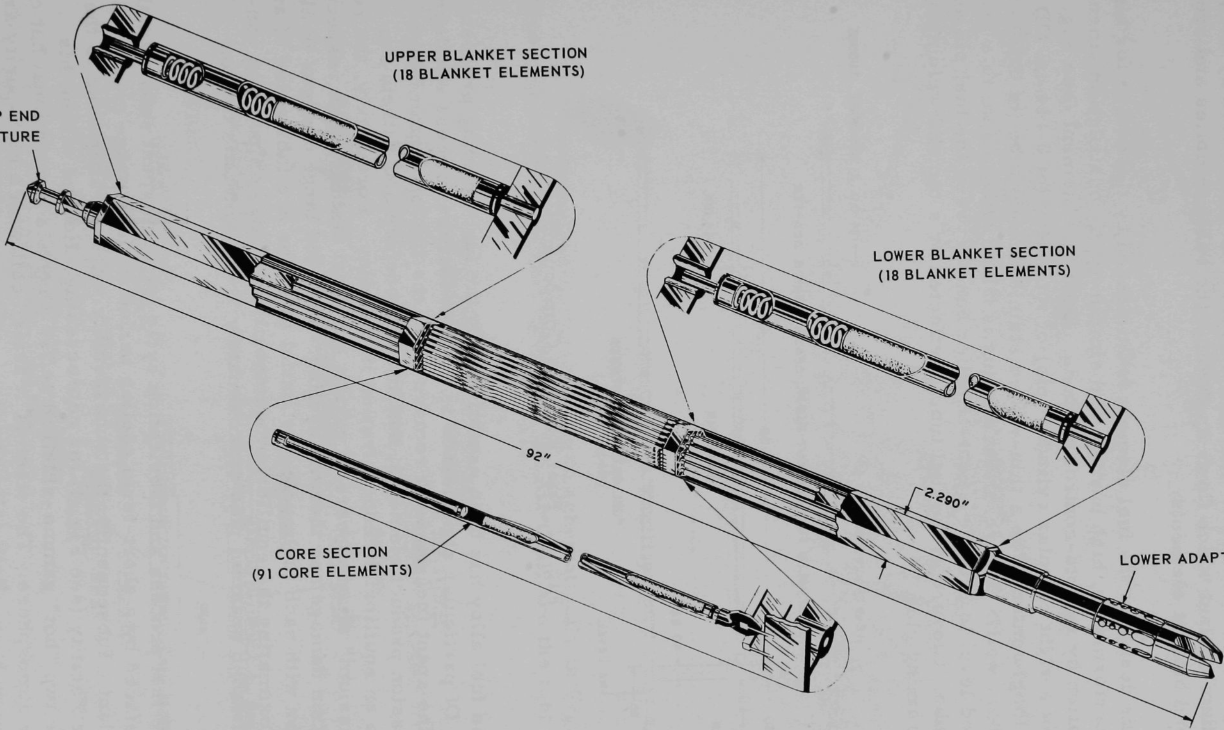

Fig. 2. Core Subassembly
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The heat generated in the fuel (or blanket) material is removed by the primary sodium coolant which flows up through the subassemblies and around the fuel and blanket elements.

The design of the fuel element is influenced by the desire for high thermal performance, high burnup, and simplicity of construction amenable to fabrication by remote-control methods. Each fuel element (see Fig. 3) consists of a right circular cylinder (pin) of fuel alloy (of 0.144-in. OD and 14.22 in. long) contained in a thin-walled stainless steel tube (of 0.156-in. ID and 0.009-in. wall). The resultant annulus is filled with sodium to a predetermined level to provide a heat-transfer bond between the fuel pin and the fuel tube. Closure of the fuel tube is effected by a top end welding and fuel-restraining plug.

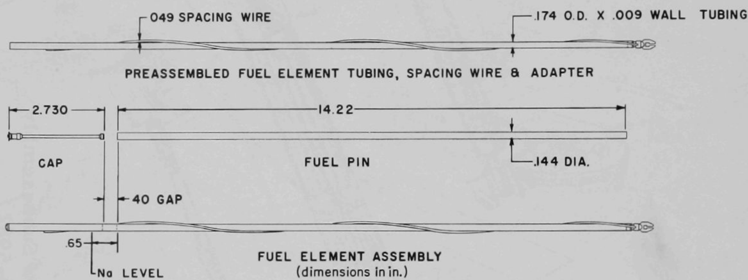

Fig. 3. Fuel Element Components
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The fuel alloy has been established by the fuel-refining process selected. Of particular significance is the fact that the process employed to refine the spent fuel does not remove all of the fission contaminants. Certain fission product elements, notably molybdenum and ruthenium, build up to an equilibrium concentration in the alloy. Fortunately, the resultant "fissium" alloy appears to exhibit excellent stability with respect to irradiation damage and thermal cycling. To avoid large changes in alloy composition with each fuel cycle, the initial fuel pins are fabricated of an alloy approximating the equilibrium composition. This composition consists of enriched uranium plus approximately 5 w/o synthetic fission products.

The fuel process and fabrication cycle for each spent subassembly will be prefaced by a short-term cooling period in the storage area of the Reactor Plant. Subsequently, the subassembly will be transported to the Fuel Cycle Facility (see Fig. 4) for reprocessing. Housed within this facility are two "hot" gamma-shielded cells. One is a conventional hot cell with an air atmosphere. The other is a sealed cell with a high-purity argon gas atmosphere. Both cells have been designed to contain the machinery for continuous, remote-controlled reprocessing of the reactor fuel.

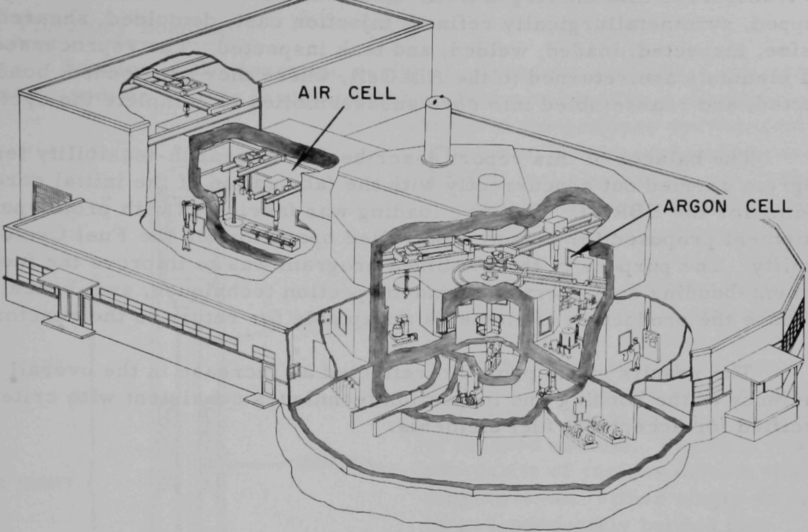

Fig. 4. Fuel Cycle Facility
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The fuel-processing cycle is shown schematically in Fig. 5. The spent subassembly is disassembled in the Air Cell, and the fuel elements

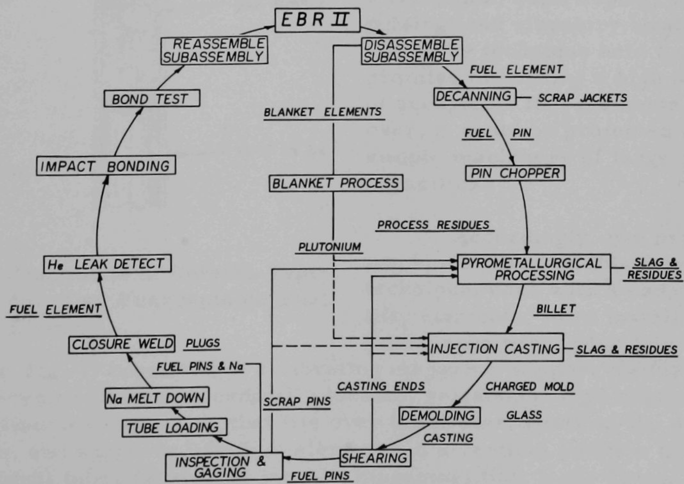

Fig. 5. Schematic of Fuel-processing Cycle
106-5981 Rev.

are transferred into the Argon Cell. Here, the fuel elements are decanned, chopped, pyrometallurgically refined, injection cast, demolded, sheared to size, inspected, loaded, welded, and leak inspected. The reprocessed fuel elements are returned to the Air Cell, where they are bonded, bond inspected, and reassembled into core subassemblies to complete the cycle.

The balance of this report describes the research-feasibility test program carried out concurrently with the fabrication of the initial core loading for the EBR-II. The core loading was fabricated with prototype equipment proposed for remote-controlled operations in the Fuel Cycle Facility. The purpose of the combined program was to improve the fuel element-bonding equipment and bond-inspection techniques, and, hence, to increase the production of elements acceptable for return to the reactor.

The results of the program reflected an increase in the overall efficiency of the bonding and inspection techniques consistent with criteria specified for acceptable fuel elements.

II. BONDING

A. Vibratory Bonding

Bonding is the operation designed to produce a uniform, gas-free, annular sodium bond to insure maximum heat transfer from the fuel element to the primary system coolant. The criteria for acceptable bonds in EBR-II fuel elements are: (1) that the annulus be clear of all gas bubbles or void areas greater than $\frac{3}{16}$ in. long and $\frac{1}{16}$ in. wide; (2) that the sodium be in wetted contact with the surface of the fuel pin and the inner surface of the fuel tube; (3) that the level of the sodium extend 0.65 ± 0.10 in. above the fuel pin; and (4) that the gas pocket be clear of trapped sodium. Figure 6 is a composite of various defects that might prevail, either singly or jointly, in an inadequately bonded fuel element.

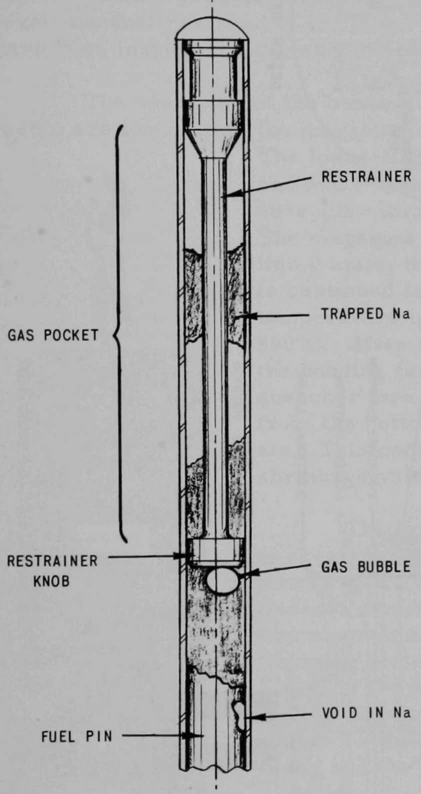

Fig. 6. Composite of Defects Typical of an Unacceptable Fuel Element.

Several methods of bonding the elements were evaluated in an independent study.[1] These included: furnace bonding; submerged canning; ultrasonics; centrifuging; pressure pulsing; and vibratory bonding. The vibratory technique held the greatest promise of bonding a high percentage of acceptable fuel elements. Moreover, it could be projected to fairly simple machinery of large production capacities.

Accordingly, two prototype machines based on this bonding technique, each with a capacity of fifty elements, were installed on the initial core production line. Each unit (see Fig. 7) consisted of a vibrating magazine-support platform driven by a 60-cycle vibrator; a centrally located, resistance-type heater coil; a right cylindrical magazine that fits over the heater, rests on the vibrating platform, and supports fifty fuel elements in a vertical position by means of individual tubes fabricated into the magazine; fifty loose-fitting sockets

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[1] E. S. Sowa and E. L. Kimont, Development of a Process for Sodium Bonding of EBR-II Fuel and Blanket Elements, ANL-6384 (July 1961).

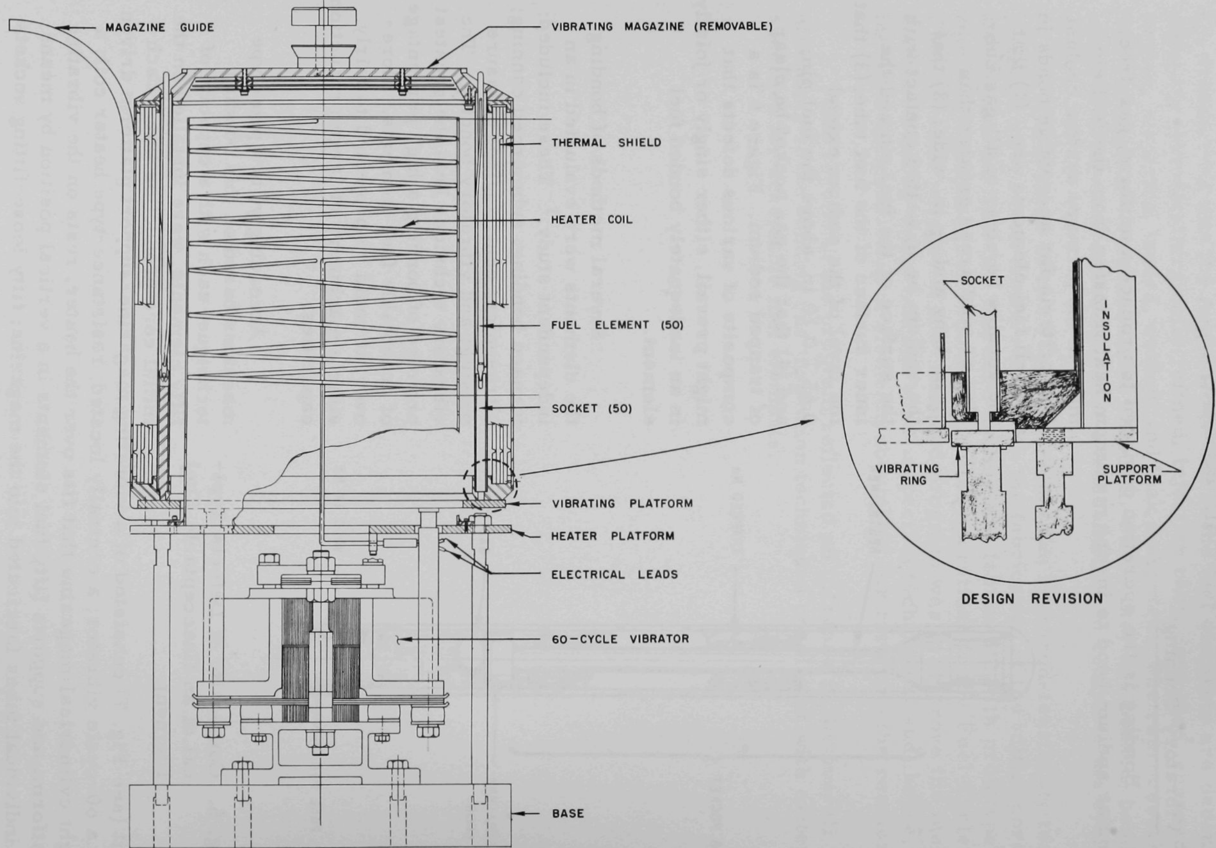


Fig. 7. Vibratory Bonding Furnace Assembly

that support the elements in the horizontal plane and are the connecting link between the vibrating platform and the element; and the necessary hardware and electrical controls for operation of the machines.

The fuel elements, as delivered to the bonding machine, are completely assembled: the fuel pins are contained in measured cladding cans together with a predetermined amount of sodium to insure a proper sodium level; the fuel restraining end plugs are welded in place; and the elements have been inspected for leaks and gross misalignment.

The operation of the bonding equipment is as follows: The fuel elements are loaded into the magazine and placed on the vibrating platform. The loose-fitting sockets extend through the magazine and make contact with the plate connected to the 60-cycle vibrator at the base of the furnace assembly. The magazine is heated and, when the sodium is in a liquid state, the vibrator is turned on. This action is continued for 2.5 hr. During this time, the furnace temperature is brought to a steady-state value of 500°C. After the run, the magazine is removed from the bonding furnace and placed on a "quencher." The quencher (see Fig. 8) progressively cools the elements from the bottom to the top by controlled flow of cool air. This controlled cooling clears the elements of shrinkage voids.

Fig. 8.

Fuel Element Bonding Magazine Being Lowered onto Air-cooling Quencher.

The foregoing process relies on two factors to create a well-bonded fuel element: (1) a temperature of 500°C to insure wetting of the sodium to the internal surfaces; and (2) the energy imparted to the fuel element as it is bounced off the high-frequency vibrating plate. The large-amplitude, low-frequency flights of the element are important to the bonding effort. Check-out test operation of the vibratory bonder revealed these flights were random in occurrence and the amplitudes ranged from 0.25 in. to 0.375 in.

During the early stages of the production run, both machines were plagued with equipment failures and erratic performance. The lack of reliability was attributed to inability of the machines to vibrate the heavy magazine. Therefore, certain design revisions were made whereby the vibratory energy was imparted directly to the fuel element. These revisions (see inset of Fig. 7) included replacement of the vibrating platform with a vibrating ring, counterboring the magazine base to allow clearance for the ring, and placement of the magazine on a stationary base. As a result of these changes, both machines accumulated approximately 19,560 bonding cycles without equipment failure. However, the production performance of the machines continued to be erratic. Consequently, a considerable number of fuel elements were recycled (in some instances, several times) to achieve acceptable bonds. On the average, 1.4 bonding cycles were required to produce one acceptable fuel element.

This initial production experience with the vibratory bonding equipment, along with visual examination of the processed fuel elements, revealed: (1) impulses that promoted free, uninterrupted flights of the elements from and to the vibrating plate, and (2) amplitudes of from 0.25 in. to 0.375 in. were conducive to the production of acceptable bonded fuel elements. Amplitudes in excess of 0.375 in. resulted in sodium entrapment in the gas-pocket area of the element. Moreover, there was a definite change in the random frequency with which these amplitudes could be achieved (possibly due to cocking and/or friction between the fuel element and support tube). These observations suggested a timed-impact mechanism that would: (1) deliver a sharp blow to the base of the fuel element and, indirectly, impart motion to the contained fuel pin; and (2) allow the fuel pin to settle prior to the next impact.

B. Impact Bonding

Figure 9 shows the laboratory test model of the timed-impact bonding equipment. It comprised: (1) a thermally controlled furnace section (24 in. long) with an internal diameter (2 in.) surrounded to full length by Hevi-Duty heaters; (2) a steel striking head actuated by an air cylinder (of 2.5-in. dia); (3) an electrical timer for operating the air-control valve and, in turn, the air cylinder; and (4) fuel-element holders.

Two types of fuel-element holders were evaluated. The "Fixed Element" holder held six elements snugly, and the blow from the driving head was imparted to the holder. In this case, the holder moved with the element, thus eliminating the cocking effect and the friction observed in the production machinery.

The "Tube Type" holder was a small mockup of the production magazine. Three fuel elements, with connecting sockets attached, were placed into the tubes, and the elements received the impact directly through the socket. The "Tube-Type" holder was used to investigate the practicality of using it in conjunction with the impact-bonding technique and the proposed remote-controlled operations in the Fuel Cycle Facility.

Each holder was top loaded into the furnace, supported by the handle resting on the top of the furnace, and extended through the open bottom of the furnace. The amplitude of the free flight was varied by adjusting the conflict between the striking head and the holder. In the case of the "Fixed Element" holder, this was done by rotating the hexagonal nut at the bottom. On the "Tube-Type" holder, the adjustment was made at the handle.

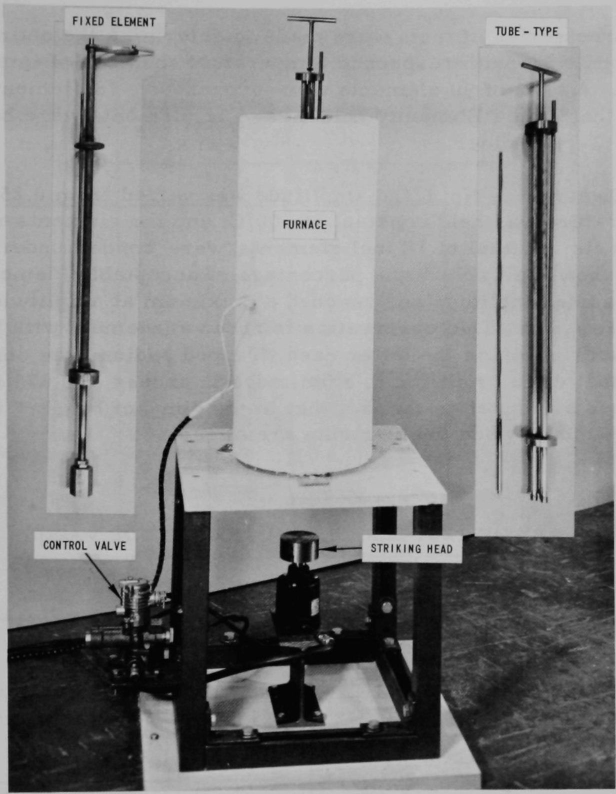


Fig. 9. Timed-impact Bonder and Fuel-element Holders

Upon completion of each bonding operation, the elements were quenched on the production line and inspected by normal production methods, i.e., by use of eddy-current technique for void detection, and by use of X rays for bubbles and gross traps in the restrainer area.

The impact bonder was initially employed in an attempt to recover fuel elements that had been rejected from the production line. These rejects, totalling 123 fuel elements, had been recycled several times through the production machine without success. Also, they represented the full spectrum of bond defects (see Fig. 6). The impact bonder was set for a temperature of 500°C, a flight amplitude of 1.5 in., and 500 impacting blows per element. The "Fixed Element" holder was employed throughout the recovery program. The results were very encouraging: 116 fuel elements were recovered, for an overall yield of 94%.

Three series of tests were made to determine the optimum impact-bonding conditions with respect to temperature, number of impacts, and amplitude. A total of 90 elements were processed: 78 elements were bonded in the "Fixed Element" holder, and 12 elements were bonded in the "Tube-Type" holder.

In Test Series No. 1, the amplitude was varied from 0.25 to 1.5 in., the temperature was held constant at 500°C, and the elements received 1,000 impacts. A total of 18 fuel elements were bonded under these conditions. As shown in Table 1, the percentage of acceptable elements increased with increasing amplitude and reached a maximum at amplitudes ranging from 1.25 to 1.5 in. This observation is not in agreement with the vibratory-bonding experience. In the latter case, trapped sodium was observed in elements that were propelled to amplitudes in excess of 0.375 in. The difference is attributed to the fact that in the "impact bonder" the impacts are imparted only when the elements are at rest.

Table 1

SUMMARY OF TEST SERIES NO. 1: AMPLITUDE VARIED

Temp: 500°C; Type of Holder: "Fixed Element";
Impacts: 1000; Elements per Holder: 3

Test No.	Amplitude, in.	Element Classification (Eddy Current and X ray)		Cause of Rejection			Percent Acceptable
		Accept	Reject	Void	Bubble	Na Trap	
1	0.25	1	2	2	0	1	33
2	0.50	1	2	1	2	0	33
3	0.75	1	2	0	2	1	33
4	1.0	3	1	0	1	1	66
5	1.25	3	0	0	0	0	100
6	1.50	3	0	0	0	0	100

In Test Series No. 2, the temperature was held constant at 500°C, the amplitude was preset at 1.50 in., and the number of impacts was varied from 10 to 1000. As shown in Table 2, the maximum percentage of acceptable fuel elements was achieved with impacts ranging from 800 to 1000.

Table 2

SUMMARY OF TEST SERIES NO. 2: IMPACTS VARIED

Temp: 500°C; Type of Holder: "Fixed Element";
Amplitude: 1.50 in.; Elements per Holder: 3

Test No.	Number of Impacts	Element Classification (Eddy Current and X ray)		Cause of Rejection			Percent Acceptable
		Accept	Reject	Void	Bubble	Na Trap	
1	10		3	3	3	0	0
2	20		3	3	3	0	0
3	40		3	2	1	0	0
4	60	2	1	1	0	0	66
5	80	1	2	2	0	0	33
6	100	1	2	2	0	0	33
7	150	1	2	2	0	0	33
8	200	1	2	2	0	0	33
9	300	3	0	0	0	0	100
10	400	2	1	1	0	0	66
11	500	2	1	1	0	0	66
12	600	1	2	1	1	0	33
13	700	2	1	1	0	0	66
14	800	3	0	0	0	0	100
15	900	3	0	0	0	0	100
16	1000	3	0	0	0	0	100

In Test Series No. 3, the machine was preset for an amplitude of 1.50 in., a total of 1000 impacts per holder, and the temperature was varied from 250°C to 500°C. As evidenced by Table 3, the maximum number of acceptable fuel elements was achieved with a bonding temperature of 500°C.

Table 3

SUMMARY OF TEST SERIES NO. 3: TEMPERATURE VARIED

Amplitude: 1.50 in.; Type of Holder: "Fixed Element";
Impacts: 1000; Elements per Holder: 3

Test No.	Temp, °C	Element Classification (Eddy Current and X ray)		Cause of Rejection			Percent Acceptable
		Accept	Reject	Void	Bubble	Na Trap	
1	250	0	3	3	0	1	0
2	300	0	3	3	0	1	0
3	350	2	1	1	0	1	66
4	400	1	2	2	0	0	33
5	450	2	1	1	0	0	66
6	500	3	0	0	0	0	100

The impact-bonding test program was terminated with the bonding of twelve fuel elements, using the "Tube-Type" holder. The machine was preset for a temperature of 500°C, a total of 1,000 impacts per element, and an amplitude of 1.875 in. The results were excellent: eleven perfect elements, and one element with a small, acceptable void.

As a final verification of the bonding ability of this technique, groups of elements were selected from each test series and decanned for visual inspection. Elements bonded at 250°C revealed porous and cracked sodium, and incomplete wetting of internal surfaces. Trapped sodium occurred in most elements bonded at temperatures below 400°C. Elements bonded at temperatures above 400°C showed a homogeneous sodium annulus, characteristic of complete wetting of surfaces. The same condition prevailed in elements bonded with amplitudes as low as 0.375 in.; however, bubbles were observed under the restrainer in these elements. No bubbles were detected in elements bonded with amplitudes of 1.5 in.

The following conclusions are based on the results of the test program, and the experience gained from the prototype production bonding machine:

(1) Acceptable bonds can be produced consistently, in a shorter operational time, by using a bonding temperature of 500°C, an amplitude of 1.50 in., and a total of 1,000 impacts per element.

(2) The impact-bonding technique can be used without disturbing or changing the proposed remote-controlled handling scheme in the Fuel Cycle Facility.

III. BOND INSPECTION

During the early stages of Core-I production, the fuel elements (at room temperature) were inspected with an eddy-current coil and a semi-remote-controlled machine. The equipment is shown in Fig. 10.

Briefly, the inspection procedure was as follows: The bonding magazine containing 50 elements was removed from the quencher and lowered onto the indexing platform. The indexing platform positioned a single element under the eddy-current coil. The push rod raised the element up through the coil for complete scanning, then reversed direction and allowed the element to fall back through the coil to complete the inspection cycle. This cycle was repeated automatically until the entire magazine inventory was inspected.

The specifications for the initial detection coil were: 0.438-in. ID; 0.0938 in. long; 250 turns of Formvar-insulated, AWG-40 copper wire; and a frequency of 90 kc. The coil was connected to a DuMont Cyclograph.

The apparatus was durable and capable of detecting inhomogeneities in the sodium annulus that were smaller than the specified maximum non-wetted area. However, it could not: (a) differentiate between gas-filled voids and shrinkage voids created by improper cooling; or (b) accurately define the sodium level.

The latter specification was difficult to meet under production conditions because of the close tolerances of the element and the thermal behavior of the fuel pin. A total accumulated fabrication error of 0.001 in. between the ID of the clad and the OD of the fuel pin can reflect a differential of 0.04 in. from the specified sodium level. Moreover, during the preheating stage of the bonding operation, varying amounts of retained gamma phase in the fuel pin are converted to the more dense alpha phase, with a consequent change in volume. Destructive examination of certain production fuel elements revealed diametrical reductions ranging from 0.0001 in. to 0.0006 in., and longitudinal reductions from 0.010 in. to 0.060 in.

Consequently, drastic changes in the sodium level did occur. Attempts to predict the sodium level on the basis of dimensional data at time of loading were unsuccessful. In the absence of an accurate measuring device, and as a matter of expedience, the sodium level in Core-I fuel elements was determined by X-ray techniques.

X-ray bond-inspection techniques are not amenable to remote-controlled operations in the Fuel Cycle Facility. Moreover, the inspection will be performed with fuel elements containing bond sodium in the liquid state. Accordingly, experimental equipment was assembled to facilitate evaluation of eddy-current resolution of defects in liquid sodium.

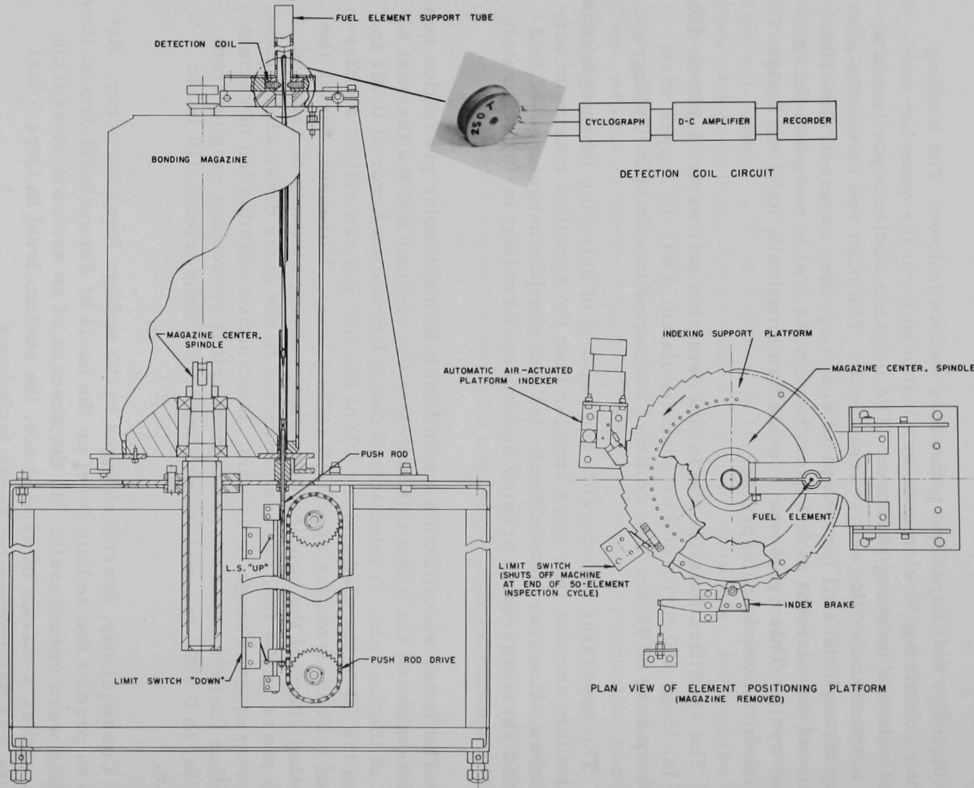


Fig. 10. Production Eddy-current Equipment Used to Inspect Fuel Elements with Sodium Bond in the Solid State

The experimental apparatus was constructed to have the same characteristics as the final "in-cell" equipment and still be versatile enough for test purposes. With reference to Fig. 11, the apparatus consisted of: (1) a single-element, two-section furnace; (2) an element drive mechanism similar to the unit used on the production line; (3) an eddy-current detection coil connected to a DuMont Cyclograph; (4) an amplifier and pen strip recorder; and (5) the necessary power-control and temperature-recording instrumentation.

Both furnace sections and the detection coil were serviced by individually controlled heaters. In this manner, the temperature along the furnace axis could be varied or maintained at a ±5°C differential, duplicating any temperature environment that may prevail in the Fuel Cycle Facility. Thermocouples were installed at 2-in. intervals along the linear axis to register temperature profiles of the entire system. The bottom furnace section was stationary. The top section could be shifted upward to permit changing of the detection coil.

Each detection coil tested was wound on the same form and with the same material used on the production machine. The fuel element was driven through the coil at 2 in./sec. Sufficient clearance was provided in the coil to eliminate any sticking or binding due to small bends or misalignment in the fuel elements.

The signal from the coil was conducted through 32 ft of 4-conductor, magnesium-insulated cable, through a variable air-gap condenser (13.5 to 320 mmf), and into the cyclograph. The transmission cable was similar to the cable that will be used to penetrate the shielding walls of the Fuel Cycle Facility. The output of the cyclograph was monitored by a dc voltmeter and fed into an amplifier where it was amplified to drive the strip recorder.

A. Resolution of Sodium-bond Defects

The first coil tested was identical with the coil used to inspect "cold" fuel elements on the production line (250 turns, 90 kc). The results were unsuccessful due to loss of coil sensitivity as the sodium became molten.

To regain sensitivity, a series of tests were made with various coil designs, operational frequencies, and coil windings ranging from 100 to 150 turns. These coils were evaluated through use of a fuel element in which only the lower half of the pin was immersed in sodium. This insured a large, unbonded, gas-filled void that was unaffected by temperature changes. The maximum difference in signal output between the bonded and the unbonded areas was obtained with a 125-turn coil operated at a frequency of 130 kc.

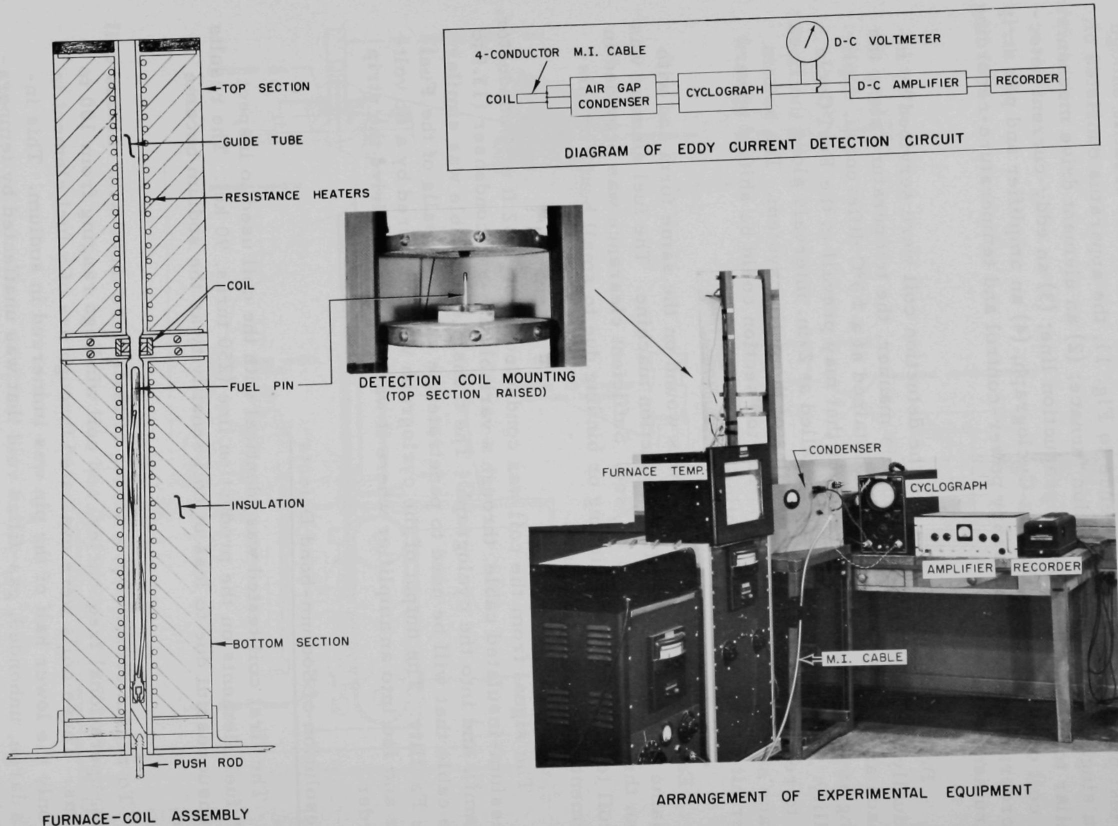


Fig. 11. Experimental Eddy-current Equipment Used to Inspect Fuel Elements with Sodium Bond in the Liquid State

The resolution of this coil was checked through use of standard fuel elements with foreign material inserts to simulate voids. In some elements, the inserts were mounted flush with the fuel pin; in others, the inserts extended 0.005 in. into the sodium annulus. The fabrication details and other pertinent data on the insert materials are described in Fig. 12 and Table 4. The criteria for material selection were: (1) resistance to attack by molten sodium, and (2) electrical resistivity lower than that of a natural void in the sodium. The eddy-current coil senses the change in resistance produced by a void in the sodium annulus. It was believed that, if the artificial voids could be resolved, natural voids of a size smaller than specified as acceptable also could be resolved.

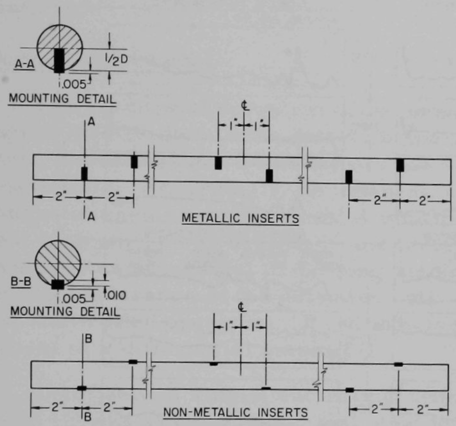


Fig. 12

Metallic and Nonmetallic Inserts Used to Simulate Voids in Fuel Elements

112-699

Table 4

DESCRIPTION AND LOCATION OF SIMULATED VOIDS IN FUEL ELEMENTS

Inserts per Fuel Element	Insert Material	Location and Geometry of Insert				Distance into Sodium Annulus, in.	Resistance, ohm-cm
		Bottom Half of Fuel Element		Top Half of Fuel Element			
		Circular, in.	Rectangular, in.	Circular, in.	Rectangular, in.		
6	Aluminum	1/64		1/32		0.000	4×10^{-6}
6	Aluminum	1/64		1/32		0.005	4×10^{-6}
6	Aluminum	1/16		3/32		0.000	4×10^{-6}
6	Aluminum	1/16		3/32		0.005	4×10^{-6}
6	Nichrome	1/64		1/32		0.000	100×10^{-6}
6	Nichrome	1/64		1/32		0.005	100×10^{-6}
6	Nichrome	1/16		7/64		0.000	100×10^{-6}
6	Nichrome	1/16		7/64		0.000	100×10^{-6}
4	Graphite (Reactor Grade)	1/16	1/16 x 3/32	3/32	1/16 x 1/8	0.005	830×10^{-6}
4	Lava "M" (Fired)	1/16	1/16 x 3/32	3/32	3/32 x 1/8	0.005	9×10^{11}
4	Lava "A" (Fired)	1/16	1/16 x 3/32	3/32	3/32 x 1/8	0.005	6×10^{11}

Note: Resistance of the Uranium-5% Fissium Alloy = 65×10^{-6} ohm-cm.

Resistance of Na at 140°C = 11×10^{-6} ohm-cm.

The fuel elements containing the artificial voids were inspected at 50°C, 130°C, and again at 50°C. The nonmetallic voids gave a variety of indications. Moreover, destructive analysis revealed that, in some cases, the graphite and the lava materials had been impregnated by the sodium. The metallic voids gave excellent indications. Aluminum inserts of $\frac{1}{16}$-in. diameter or larger, both flush and extended, were resolved at 130°C (see Fig. 13). Only the extended inserts were detected at 50°C. The extended nichrome inserts of $\frac{1}{16}$-in. diameter or larger were resolved at both temperatures. It was concluded that the DuMont Cyclograph, with a 125-turn coil operated at 130 kc, can resolve a void smaller than $\frac{1}{16}$ in. in diameter in the sodium annulus at 130°C.

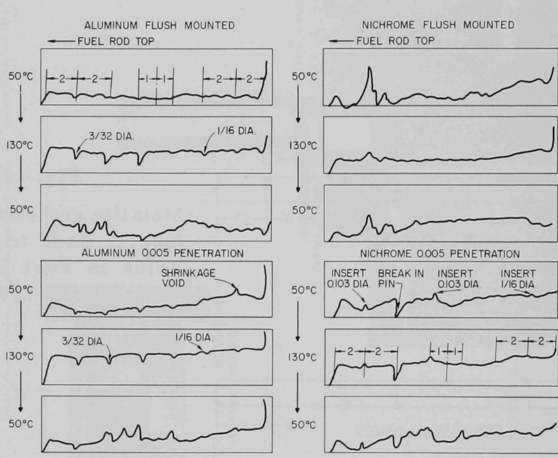


Fig. 13. Typical Cyclograph Traces of Fuel Elements Containing Aluminum and Nichrome Inserts to Simulate Voids
112-713

This conclusion was verified by a comparison inspection of elements selected from the Core-I production run. Figure 14 shows two traces of a particular production fuel element. One trace was made at room temperature with the production equipment, and the other at 130°C with the experimental equipment. This element was selected because it represented the poorest indication discernible with the production equipment. Subsequently, the element was decanned to expose the area of the fuel pin wherein the void was detected. The area was photographed and correlated to the traces. As shown in Fig. 14, the diameter of the void measured approximately $\frac{1}{16}$ in.

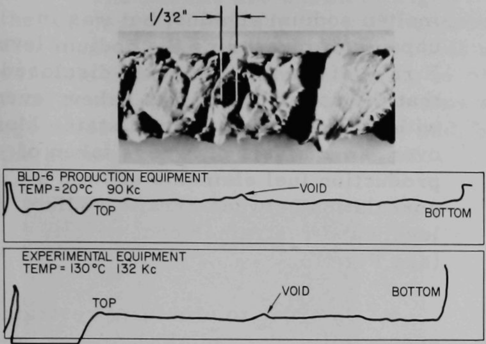


Fig. 14

Comparison of Resolutions of Void Area in Fuel Pin by Production Equipment and by Experimental Equipment

112-710

B. Sodium-bond Level

The successful operation of the experimental bond-inspection equipment was limited to the detection and resolution of defects in the sodium. Indications and definitions of the sodium level were still erratic and inaccurate. Accordingly, an independent study was made of eddy-current measurement techniques. A multipoint, differential, pulsed eddy-current instrument was designed[2] and tested on the production line. The instrument was successful in defining the sodium level; however, because of the close tolerance of the detection coil, it was deemed too delicate for remote-controlled operation. It did, however, focus attention on the development of a differential pulse coil.

Ultimately, a single, encircling, differential, pulsed eddy-current coil (see Fig. 15) was assembled and tested on the experimental bond-inspection equipment. The coil was capable of detecting a small ($< \frac{1}{16}$ in.) void in the

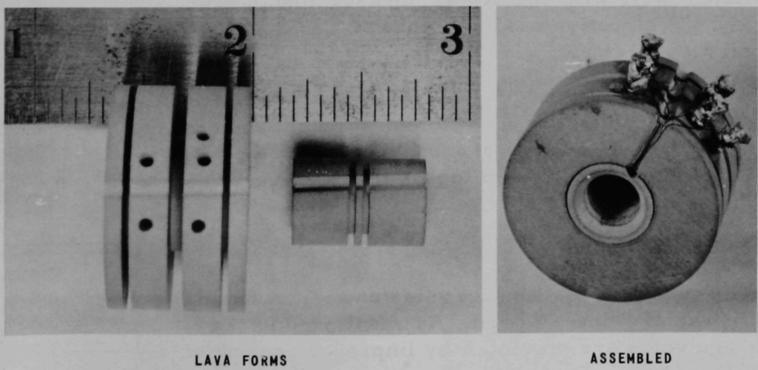


Fig. 15. Pulsed Eddy-current Coil

[2] K. Ono and W. J. McGonnagle, Pulsed Eddy-current Instrument for Measuring Sodium Levels of EBR-II Fuel Rods, ANL-6278 (July 1961).

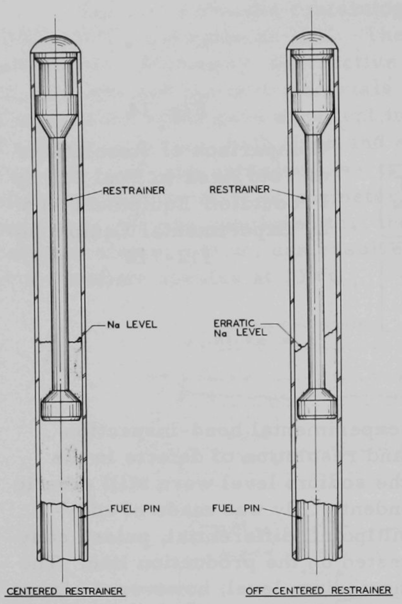


Fig. 16. Effect of Eccentricity of Fuel-pin Restrainer Knob on Sodium-bond Level
112-701

molten sodium annulus, but was incapable of measuring the sodium level. X rays of the fuel elements disclosed that the sodium level was askew, even with the sodium in a liquid state. Moreover, an analysis of X rays taken of production fuel elements showed a correlation between erratic sodium levels and restrainer eccentricity (see Fig. 16).

In order to eliminate restrainer eccentricity, the radial clearance between the lower knob and the can wall was reduced to 0.002 in. This was accomplished by increasing the diameter of the knob from 0.140 in. to 0.152 in. In addition, the knob was slotted to provide gas passages (see Fig. 17).

Fifty fuel elements were fabricated with the modified restrainers, bonded, and inspected. X rays of these elements, in the liquid and the solid states, showed uniform sodium levels. These findings were confirmed upon removal of the cladding. Figure 18 shows the uniform sodium bond level effected by the modified restrainer knob. Eddy-current measurements of these sodium levels were made with the single, differential pulsed coil. The results correlated well with the X-ray measurements (see Fig. 19). Destructive analysis showed the accuracy of level measurement to be $\pm \frac{1}{64}$ in.

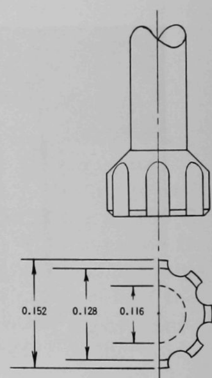


Fig. 17. Modified Lower Restrainer Knob

Further testing of the coil revealed that it was capable of detecting insufficient sodium, sodium trapped in the gas pocket, gas bubbles under the restrainer, and gas bubbles on top of the uranium (see Fig. 20).

C. Shrinkage Voids

The effect of shrinkage voids on sodium homogeneity was also investigated. As mentioned earlier, shrinkage voids are promoted by improper cooling of the sodium bond. For test purposes, a fuel element originally clear of shrinkage voids was deliberately cooled to generate voids of this type. It was inspected while the sodium was heated and cooled through the solid-liquid phase change.

The results are shown in Fig. 21. At 30°C, voids are evident. As the temperature exceeds the melting point of sodium (98.7°C), the voids disappear. Upon cooling, two new voids are visible (90°C). Both are discernible upon subsequent heating up to ~100°C, but disappear during the final cooling cycle. These observations support the conclusion that shrinkage voids are of a transient nature and, hence, do not permanently disturb the homogeneity of the sodium bond.

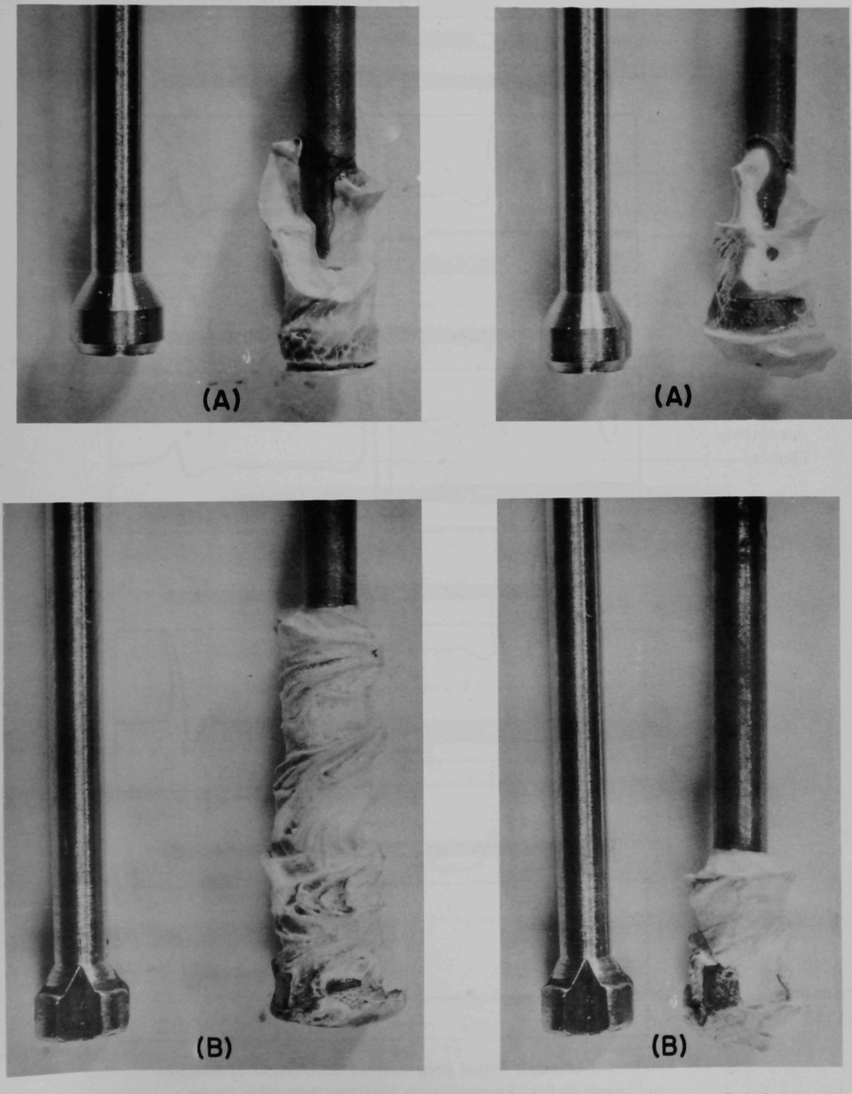
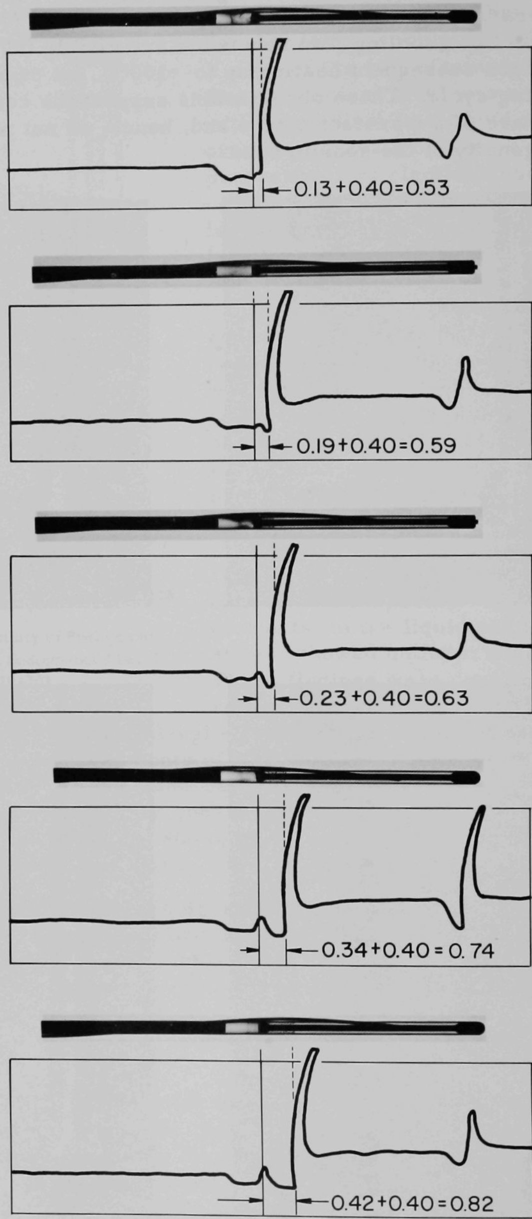


Fig. 18. Closeup of (A) Irregular Sodium Bond Level above Old Restrainer Knob and (B) Uniform Sodium Level Obtained with Modified Restrainer Knob



Acceptable Element

(dimensions in in.)

Fig. 19. Single, Differential, Pulsed Eddy-current Coil Traces of Sodium-bond Levels in Fuel Elements with Modified Restrainer Knobs
112-756

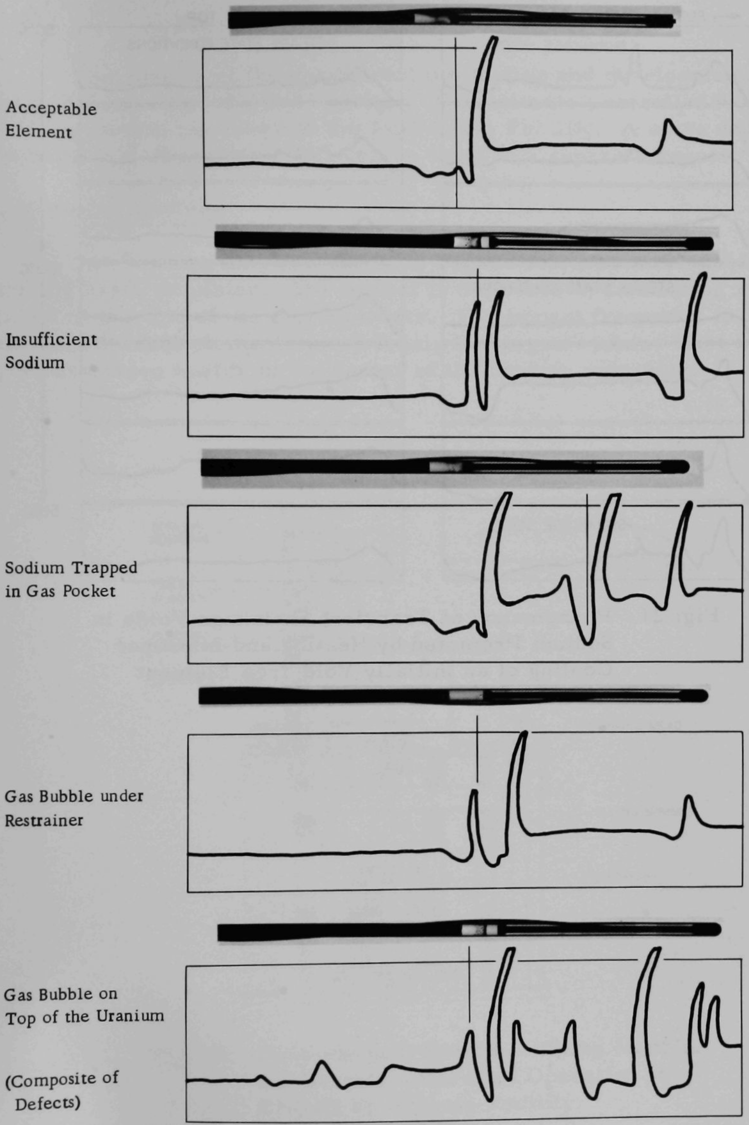


Fig. 20. Scope of Defects Detected by Single, Differential, Pulsed Eddy-current Coil
112-755

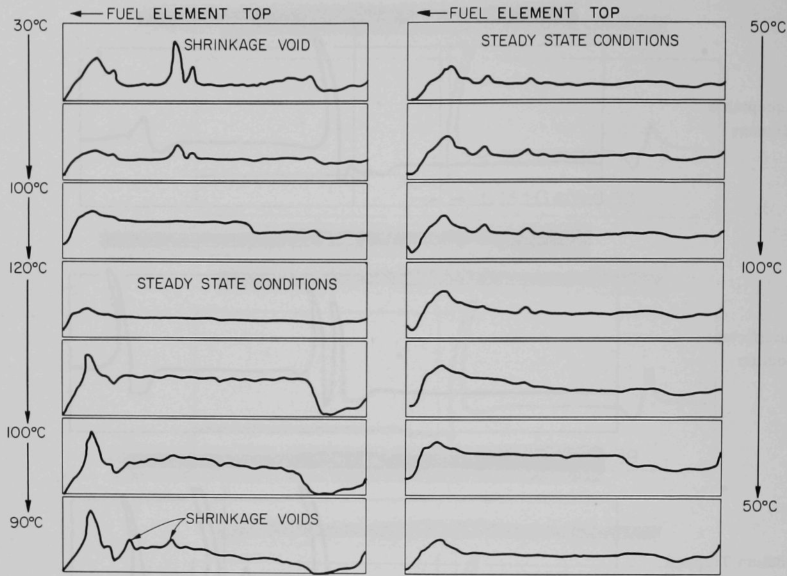


Fig. 21. Phenomenon of Transient Shrinkage Voids in Sodium Promoted by Heating and Improper Cooling of an Initially Void-free Element
112-704

IV. FUEL CYCLE FACILITY MACHINES

The results of the concurrent production and development programs were projected into the final designs of the remote-controlled bonding and bond-inspection machines in the Fuel Cycle Facility. A more detailed description of these machines can be found in a separate report.[3]

A. Bonding Machine

The bonding machine shown in Fig. 22 features a solenoid-actuated striking head, or platen. The impact is delivered to connecting rods attached to the tips of the fuel elements. The impact frequency is 30 cycles/min, and the fuel elements move freely inside guide tubes. Heat is supplied by a resistance heater in the center of the bonding magazine.

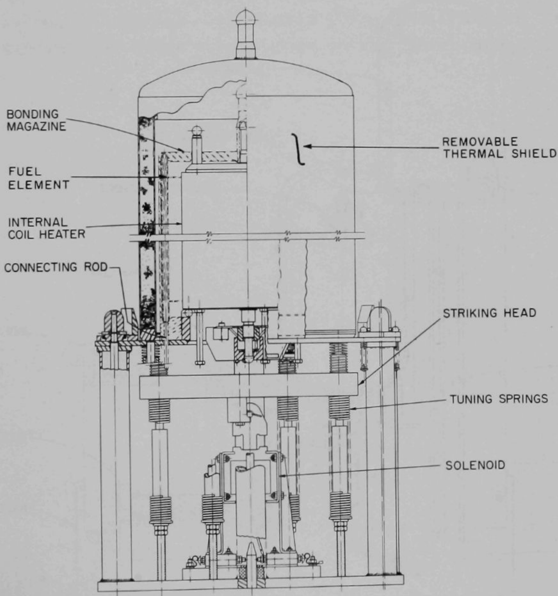


Fig. 22. Fuel-element Sodium-bonding Machine for Remote-controlled Operation in EBR-II Fuel Cycle Facility.
112-706

[3] A. B. Shuck et al., Remote Control Equipment for Refabrication of Irradiated EBR-II Fuel, ANL-6273 (to be published).

B. Bond-inspection Machine

The bond-inspection machine (see Fig. 23) employs pulsed eddy-current instrumentation. With reference to Fig. 23, the machine consists of a pivoted loading-and-indexing platform and shell heater to support the bonding magazine and to maintain the sodium in a liquid state during inspection. Other components include: (a) a magazine-indexing device which positions each fuel element under the detection coil; (b) a starter cylinder that places the element into the gripping device attached to the actuator band; and (c) a motor that drives the band, thus moving the fuel element through the detection coil. After inspection is completed, the platform is pivoted by the air cylinder, and the magazine is removed. The acceptable fuel elements are transferred to the reassemble area (see Fig. 5). The defective fuel elements are decanned and recycled.

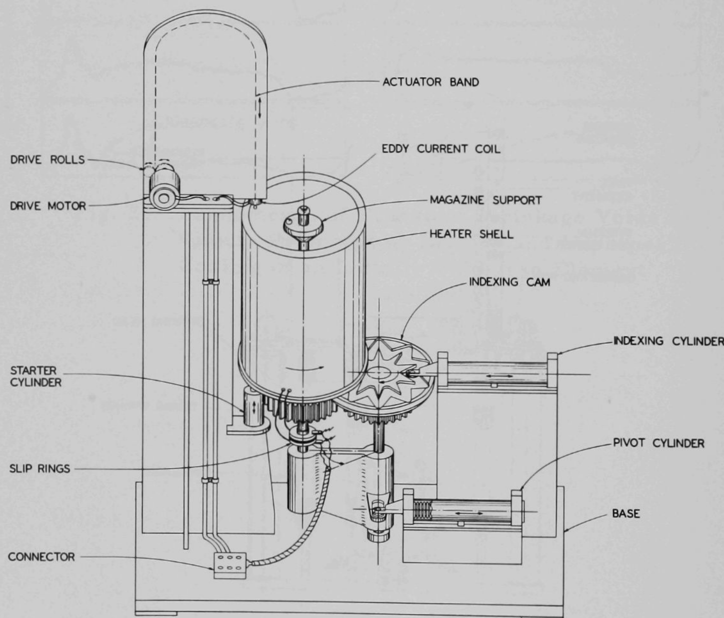


Fig. 23. Fuel-element Sodium-bond-inspection Machine for remote-controlled Operation in EBR-II Fuel Cycle Facility
112-753

The bond and bond-inspection machines are designed to have a maximum number of parts replaceable by a remote-controlled manipulator using a common grip and vertical motion.

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